A valve stiction tolerant formulation of MPC for industrial processes

Riccardo Bacci di Capaci*,**, Marco Vaccari*, Gabriele Pannocchia*

*Department of Civil and Industrial Engineering, University of Pisa, Pisa, Italy
**e-mail: riccardo.bacci@ing.unipi.it

Abstract: This paper presents three different formulations of MPC to face static friction in control valves for industrial processes. A pure linear formulation, a stiction embedding structure, and a stiction inversion controller are designed. The controllers are derived for SISO systems with linear process dynamics, where valve stiction is the only nonlinearity present in the control loop. A novel smoothed stiction model is introduced to improve and fasten the dynamic optimization module of stiction embedding MPC. A stiction compensation method is revised and used as a warm-start to build a suitable trajectory for the predictive controller. The different MPC formulations are tested and compared on some simulation examples.

© 2017, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.

Keywords: Process control; model predictive control; control valve; stiction; stiction compensation

1. INTRODUCTION

Control valves are the most commonly used actuators in the process industries. Unfortunately, in many cases valves not only contain static nonlinearity (e.g. saturation), but also dynamic nonlinearity including backlash, friction, and hysteresis. Deadband due to backlash and mostly static friction (stiction) is a root source of the valve problems. As a consequence, these malfunctions would produce a sustained oscillation in the process variables, decrease the life of control valves, and generally, lead to inferior quality end products by causing reduced profitability (Jelali and Huang, 2010). Therefore, it seems that the potential benefit of advanced control algorithms, as model predictive control (MPC), could be reduced because of poor valves, if their faults and malfunctions are not expressly considered.

MPC has in fact been also used as a compensation strategy for several types of valve malfunctions. The first MPC-based formulation was developed by Zabiri and Samyudia (2006), by using a mixed-integer quadratic programming (MIQP) on constraints of the input. An inverse backlash model and valve saturation are incorporated in the controller to overcome the deadband associated with backlash. Later, this structure is applied to a system with stiction in Zabiri and Samyudia (2009). In Rodríguez and Heath (2012) a formulation which reduces the bounds on optimization variables computed by the MPC, by trying to delete different types of valve nonlinearity, and by reducing the problem to a purely linear structure has been proposed. Recently, Durand and Christofides (2016) have presented an economic MPC structure which includes a detailed physical stiction model, constraints on the magnitude and rate of change of the input, and is combined with a slave controller of PI-type that regulates the valve output to its MPC set-point.

When stiction is present, the valve is not successful in following the input signals imposed by the controller. Consequently, a limit cycle is typically generated around the steady-state operating points. As suggested by previous works, one way of reducing stiction effects is to explicitly take this malfunction into account in MPC design so that an improved performance could be obtained. As many other fault tolerant approaches, an estimate of stiction amount is needed, and the sticky valve must be identified within the closed loop, especially when the system is multidimensional. For this purpose, well-established techniques of stiction detection and quantification could be used and adapted as necessary (Jelali and Huang, 2010).

This paper is focused on designing an MPC formulation that considers valve stiction explicitly, in order to compensate for its undesired effects on control systems. The controller will be derived for single-input single-output (SISO) systems with linear process dynamics, as the nonlinearity comes only from the valve. In order to improve the numerical optimization performance, a suitable smoothing of the discontinuous valve stiction model and an appropriate input sequence, derived from a stiction compensation method and used as warm-start for MPC, will be necessary. This novel methodology will be compared against standard and advanced MPC formulations using as test bench several simplified numerical examples.

The remainder of the paper is organized as follows. Different MPC approaches and valve stiction models are presented in Section 2. The proposed stiction-tolerant MPC formulation is detailed in Section 3. Some simulation examples as basis of comparison are then presented in Section 4. Finally, conclusions are drawn in Section 5.

2. PROBLEM DEFINITION

The whole plant is formed by the control valve followed by the process dynamics as depicted in Figure 1. In detail, $\chi$ is the process input, that is, the valve output; $y$ is the process output; $u$ is the MPC output, while $w$ and $v$ are two sequences of white Gaussian noise. For the sake of simplicity, the case of SISO system is studied: a nonlinearity for the valve followed by a linear dynamics for the process, thus forming a Hammerstein structure for the whole plant. Extensions to MIMO systems and nonlinear processes will be investigated in future research.
Reducing stiction effects is to explicitly take this malfunction into account. As suggested by previous works, one way of reducing stiction effects is to explicitly take this malfunction into account. Consequently, the input signals imposed by the controller. Consequently, the input signals imposed by the controller. An inverse backlash model and valve friction are incorporated in the controller to overcome the problem of change of the input, and is combined with a slave controller to linearize the process dynamics, where valve stiction is the only nonlinearity present in the control loop. A novel formulation can be written as:

\[
\begin{align*}
\chi_{k+1} &= f(\chi_k, u_k) + w_k \\
y_k &= h(\chi_k) + v_k
\end{align*}
\]

(1)

The valve output \( \chi \) represents the first component of the state vector of whole plant \( \chi_k = [\chi_{k-1}, \hat{\chi}_k]^T \), so that:

\[
\begin{align*}
\chi_{k+1} &= \begin{bmatrix}
\chi_k \\
\hat{\chi}_{k+1}
\end{bmatrix} = \begin{bmatrix}
\phi(\chi_{k-1}, u_k) \\
A\hat{\chi}_k + B\phi(\chi_{k-1}, u_k) + w_k
\end{bmatrix} \\
y_k &= C\hat{\chi}_k + v_k
\end{align*}
\]

(2)

where \( A \in \mathbb{R}^{n \times n}, B \in \mathbb{R}^{n \times m}, C \in \mathbb{R}^{p \times n}, n \) is the process model dimension, and \( m = p = 1 \), respectively. Note that the first component of state equation is given by the stiction nonlinearity, expressed by the discontinuous function \( \phi(\cdot): \mathbb{R}^m \times \mathbb{R}^m \rightarrow \mathbb{R}^m \), later discussed.

2.1 Possible MPC approaches

Three different approaches of MPC are presented and compared in this work. The first formulation is a stiction unaware controller, with a pure linear MPC formulation since it completely disregards the valve dynamics and uses only a linear process model for the whole plant (see Figure 2). Secondly, a stiction embedding MPC is considered, as shown in Figure 3. This controller is aware of the stiction presence, as it employs an extended model – both of valve and process dynamics – thus forming a nonlinear formulation (NMPC). Finally, the third approach is also aware of stiction, but it has an explicit model for the inverse dynamics of stiction \( \phi^{-1}(\cdot) \), where \( \hat{\chi} \) is the MPC output, subject to optimization, which forms input to stiction inverse model, and \( u = \phi^{-1}(\hat{\chi}) \) is the output of the whole controller. Note that, in the case of perfect stiction inversion, one should get \( \phi(\phi^{-1}(u)) = \hat{\chi} \), and then \( \hat{\chi} \equiv \chi \). This type of formulation, introduced by Rodriguez and Heath (2012), has the advantage of not only considering expressively stiction dynamics, but also reducing the controller to a linear structure, which is simply based on the process model, as in Figure 4.

Fig. 1. The closed-loop system with the (sticky) control valve followed by the process.

Valve dynamics is described by a data-driven stiction model, while the linear process dynamics is expressed by a state-space model. The whole plant dynamics in standard state-space formulation can be written as:

\[
\begin{align*}
\dot{z}_{k+1} &= f(z_k, u_k) + w_k \\
y_k &= h(z_k) + v_k
\end{align*}
\]

where \( z \in \mathbb{R}^n \) is the state vector, \( u \in \mathbb{R}^m \) is the input vector, \( y \in \mathbb{R}^p \) is the output vector, \( f: \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}^n \) is a nonlinear function, \( h: \mathbb{R}^n \rightarrow \mathbb{R}^p \) is a linear function, \( w \in \mathbb{R}^n \) is the process noise, \( v \in \mathbb{R}^p \) is the measurement noise. The inverse dynamics of stiction \( \phi^{-1}(\cdot) \) is a sort of valve positioner or valve actuator, which is used to compensate for the input \( u \).

2.2 Valve stiction modeling

Stiction in pneumatic sliding stem control valves can be described both by detailed physical models and by empirical (data-driven) models. If fast response from the valve is assumed, the transient response can be ignored and a static – but with memory – nonlinear function can be used to approximate the valve’s dynamic response, that is, only the stationary-state values of stem position are considered. Therefore, the standard empirical (He et al., 2007) or the semi-physical model (He and Wang, 2010) by He and coworkers are suitable to reproduce the valve response generated by physical stiction models without involving computationally intensive numerical integration.

In this paper, we choose to use the He’s standard model (He et al., 2007), thus including stiction in every valve move. The sticky valve has a nonlinear dynamics \( \chi_k = \phi(\chi_{k-1}, u_k) \) expressed by the following two relations:

\[
\chi_k = \begin{cases}
\chi_{k-1} + |e_k| - \text{sign}(e_k) f_d & \text{if } |e_k| > f_S \\
\chi_{k-1} & \text{if } |e_k| \leq f_S
\end{cases}
\]

(3)

where \( f_S \) and \( f_D \) are static and dynamic friction parameters, respectively, and \( e_k = u_k - \chi_{k-1} \). Note that \( e_k \) is a sort of valve position error, and \( f_S \geq f_D \) by definition. By substituting \( e_k \) and then by separating the nonlinear sign function, three different input-output relations are possible:

\[
\chi_k = \begin{cases}
u_k - f_D & \text{if } |u_k - \chi_{k-1}| > f_S, \quad u_k - \chi_{k-1} > 0 \\
u_k + f_D & \text{if } |u_k - \chi_{k-1}| > f_S, \quad u_k - \chi_{k-1} < 0 \\
u_k - f_D & \text{if } |u_k - \chi_{k-1}| \leq f_S 
\end{cases}
\]

(4)

Then, by solving the first two inequalities, one gets:

\[
\chi_k = \begin{cases}
u_k - f_D & \text{if } u_k - \chi_{k-1} > f_S \\
u_k + f_D & \text{if } u_k - \chi_{k-1} < -f_S \\
u_k - f_D & \text{if } |u_k - \chi_{k-1}| \leq f_S 
\end{cases}
\]

(5)

Therefore, the stiction nonlinearity \( \phi(\cdot) \) is formed by a set of three, relatively simple, linear and parallel relations, thus constituting a sort of switching “multi-mode” model to be integrated along with the dynamics of the process, to form a discontinuous model. Note that the proposed methodology and formulations of MPC are valid also for other types of stiction models.

3. MPC DESIGN

In this section the considered formulations of MPC are detailed, by introducing an empirical stiction inverse model, a novel smoothed stiction model, some specific choices for modules and tuning parameters, and a suitable warm-start based on a stiction compensation method.
دریافت فوری
متن کامل مقاله

امکان دانلود نسخه تمام متن مقالات انگلیسی
امکان دانلود نسخه ترجمه شده مقالات
پذیرش سفارش ترجمه تخصصی
امکان جستجو در آرشیو جامعی از صدها موضوع و هزاران مقاله
امکان دانلود رایگان ۲ صفحه اول هر مقاله
امکان پرداخت اینترنتی با کلیه کارت های عضو شتاب
دانلود فوری مقاله پس از پرداخت آنلاین
پشتیبانی کامل خرید با بهره مندی از سیستم هوشمند رهگیری سفارشات